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A WEIGHT COMPARISON OF ELECTROCHEMICAL DEVICES AND TURBINE-TYPE APU's FOR SPACE SHUTTLE ORBITER NON-PROPULSIVE POWER

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ABSTRACT

In present designs of the space shuttle orbiter, the on-board power is supplied by a fuel cell unit and a turbine APU. A weight comparison was made between this system and hypothetical ones using fuel cells or batteries to replace the turbine APU. Consideration was given to mechanical power transmission via electric motors as well as hydraulic transmission.

For hydraulic transmission, use of fuel cells plus a turbine APU led to a lower total system weight. Electrical motors with low specific weight fuel cells were comparable in weight to hydraulic systems with APU power sources.

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INTRODUCTION

As the Phase A and B studies of the space shuttle concept have proceeded, the on-board power requirements for the orbiter portion of the shuttle craft have become more clearly defined. These requirements include electrical power, both AC and DC, for avionics, environment control and life support systems; and mechanical power for actuation of the vehicle control surfaces during atmospheric flight, deployment of flyback engines, lowering landing gear, etc. All the design concepts thus far presented include various combinations of fuel cells and batteries for DC power, inverters and/or turbine-alternators for AC power, and turbine-powered hydraulic systems for mechanical power.

Because the orbiter vehicle will be very weight-sensitive, the question has arisen whether or not a weight advantage might result from the replacement of the turbine-type power sources by electrochemical devices, either fuel cells or batteries. In order to study this possibility five hypothetical power sources are considered. Two of these utilize fuel cells as the source of all power, and two use a combination of fuel cells and batteries. As a basis for comparison, the fifth consists of fuel cells and turbine-type

APU's, and represents the current thinking of contractors and NASA shuttle personnel. Two modes of control surface actuation, hydraulic and electric, are considered.

For each of these power systems, consideration is given to four different types of fuel cells, to determine whether or not any one type would provide a clear weight advantage to the total system. These four types all operate on hydrogen and oxygen. They are: Pratt and Whitney's proposed dual-mode system; Allis-Chalmer's liquid-cooled system; General Electric's acid ion-exchange membrane system; and Pratt and Whitney's closed cycle alkaline system.

It is understood that the selection of a power system for the orbiter will not be determined by weight, alone. Other factors, such as development cost and risk, time, payload value, and operating life must be considered for the orbiter as a whole. These items are not treated in this report.

ANALYSIS AND DISCUSSION

The net power requirements of the space shuttle orbiter listed in Table Ia represent a composite view obtained from the various proposals and contractor reports related to the shuttle mission studies. A "fail operational, fail safe" philosophy was adopted for this paper, leading to the redundancy level given in Table Ib, and the net power requirement per power package presented in Table Ic.

The performance capabilities and specific weights for the four types of fuel cells are listed in Table II. These data were largely obtained from the respective manufacturers and are weighted to represent our assessment of the state-of-the-art.

The component efficiencies used to determine the gross power require-
ment of each power package are tabulated in Table III; and either the
specific weight or the unit weight of each component is shown in Table IV.
These efficiencies and weights also correspond to current technology.
Table V presents a weight breakdown for the hydraulic unit and the turbine-
type auxiliary power unit, obtained from a shuttle study Phase B baseline
description by North American Rockwell.

The electric and mechanical power profiles used in this study were
also derived from the above baseline description. These profiles are
subject to change, dependent upon final decisions as to vehicle configu-
ration and design objectives, e.g., long vs. short cross-range capability.

For each power package, the power-producing components were sized
to meet their peak-power requirements when operating at their respective
maximum power capabilities. The fuel consumption of each power source
was determined from its gross power profile and the operating efficiency
at each power level in its power profile. For the fuel cell system, this
latter information was obtained from the respective polarization curves.
For the turbine APU, an average specific propellant consumption of 3.92
lb/kw-hr was taken from the North American study.

Block schematic diagrams and gross power profiles for each of the
five hypothetical power systems are presented in figures 1 through 5.
Each gross power profile reflects the effect of system component ineffi-
ciencies which must be overcome in order to meet the net power requirements
of Table Ic. All five systems take advantage of the high efficiency of
fuel cells, using them to fulfill the requirement of the largest energy
block - about 430 kilowatt-hours of DC power.

The present thinking concerning the on-board power supply for the shuttle orbiter is depicted by System A. Here the mechanical power requirements are met by a hydrogen-oxygen turbine-type APU which activates a hydraulic unit. Since the fuel cell unit in this system is designed only to the eight kilowatt level, the effect of fuel cell weight, shown in Table VI, does not have a great effect on the total weight of the power package.

In System B, fuel cells are also used as the source of hydraulic and AC power, operating a DC motor which in turn drives an alternator and a hydraulic pump. Due to the inefficiency and high fixed weight of the hydraulic unit, this power package is quite massive. Because the fuel cells must be designed to the peak power level of 97 kw, a considerable weight advantage accrues to that configuration of System B which uses the fuel cells capable of the greatest power density. This is seen in Table VII.

System C replaces the electric motor, hydraulic unit, and alternator of System B with individual electric motors at each flight control surface, and inverters. This system is more efficient and has a lower fixed weight, but Table VIII shows there is still an appreciable benefit from using the highest power density fuel cell unit. It must be noted here that an all-electric actuator system is not part of current aircraft technology.

Systems D and E are analogous to systems B and C, except that silver-zinc batteries are used instead of fuel cells as the power source for the electric motors. Tables IX and X show that, as with System A, the type of fuel cell unit used in Systems D and E has only small effect on power package weight. Comparing analogous systems reveals that a system with

batteries plus fuel cells is generally heavier than one with fuel cells

alone, except when considering fuel cell units with exceptionally conserva-

tive estimates of specific weight. When this is done, the respective

system weights are competitive.

CONCLUDING REMARKS

A summary of the total weights of the various on-board power supplies

for the orbiter vehicle, as considered in this study, are presented in

Table XI. Comparing the three systems which involve the hydraulic actua-

tion of the flight control surfaces (Systems A, B and D), it is seen that

the use of a turbine-powered APU with a fuel cell results in a lighter

system than does the use of electrochemical power sources alone.

A comparison of Systems A, C and E indicates that a weight advantage

over turbine APU/hydraulic actuation might be realized by using low specific

weight fuel cells and electric actuation. As previously mentioned, electric

actuation is not part of current aircraft technology. It may, however, be

worthy of consideration by the shuttle mission study contractors.

Comparing System B with System D and System C with System E, it is

seen that the use of batteries plus fuel cells generally results in a

higher system weight than does the use of fuel cells alone. However, for

a fuel cell unit having a high estimated specific weight, the respective

systems are equivalent in weight.

All the system weights developed in this study are, of course, subject

to change. They can be affected by alterations in the time duration or

objectives of the orbiter mission. They are dependent on the finalized

configuration of the vehicle, and its attendant power requirements.

Advancements in the state of the art may lead to drastic decreases in fuel cell engine specific weights, or increases in the energy density of batteries. Even within the constraints of this study, large weight changes could be generated by going to a different philosophy of redundancy requirements. However, the latter would probably not affect the ranking of the various system weights presented here.

SUMMARY

The approximate on-board power requirements for the present concepts of the space shuttle orbiter include 16 kw DC, 20 KVA AC and 100 HP mechanical. In current designs the DC requirement is met with fuel cells, and a turbine-type APU supplies the AC and mechanical needs through an alternator and hydraulic pump.

A weight comparison was made between such a power supply system and several others which used additional fuel cells or batteries in lieu of the turbine APU. Consideration was given to silver-zinc batteries and four types of fuel cells: the Pratt & Whitney proposed dual-mode; the Allis-Chalmers liquid-cooled; the General Electric acid ion-exchange membrane; and the Pratt and Whitney closed-cycle. Also considered was the production of mechanical power by electric motors instead of a hydraulic system, the latter representing current aircraft technology.

With hydraulic power transmission the use of a fuel cell plus a turbine APU led to a lighter system than did the use of either fuel cells alone or in combination with batteries. A system using fuel cells alone for total power generation was generally lighter than one using fuel cell-battery combinations. Low-specific weight fuel cells with

electric motor power transmission were lighter than, or comparable to the APU/hydraulic system. However, the total use of electrical actuation in place of hydraulic systems is not current aircraft practice and would constitute a new technology area for the space shuttle which would have to be studied in detail to determine its feasibility.

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Table Ia

Net Power Requirement

DC Power for EC/LSS
5 kw average; 16 kw max.

Mechanical Power for Control Surface Actuation
100 HP max.

AC Power for Engine Fuel Pumps, etc.
20 KVA

Table Ib

Redundancy

Four Power Packages On Board

Two will meet mission power requirement.
(fail operational, fail safe)

Table Ic

Net Power Requirement Per Package

DC power
2.5 kw average; 8 kw max.

Mechanical power
50 HP max.

AC power
10 KVA

Table II

Fuel Cell System Design Criteria

	Proposed Dual Mode	Closed Cycle	Allis-Chalmers [1]	General Electric
Maximum Power Density (WSF)	1356	320	165	110
Maximum Current Density (ASF)	2000	400	200	150
Minimum Voltage	0.678	0.80	0.823	0.73
Min. Thermal Efficiency	0.46	0.54	0.556	0.493
Misc. Specific Weight (lb/kw)	5.2*	22.2	34.5	16

* 7.35 lb/kw for power levels less than 10 kw

Table III

Component Efficiencies

Electric Motors	95%
Alternators	95%
Inverters	95%
Electric Transmission Lines	93% [2]
Hydraulic System (Overall)	50%
Hydraulic Transmission Lines	73% [2]
Hydraulic Pumps	83% [2]
Servo Valves and Actuators	85%

Table IV

Component Weights and Specific Weights

Electric Transmission Lines (Aluminum)	170 lb [2]
DC Motors @ 20 HP steady state	4.5 lb/HP [3]
@ 50 HP steady state	3.0 lb/HP
Inverters	15 lb/KVA
Alternators	25 lb
Tankage: Hydrogen	0.88 lb/lb [4]
Oxygen	0.10 lb/lb
Radiator	48 lb/kw
Heat Exchanger	2 lb/kw
Evaporator	2 lb/kw
Silver-Zinc Batteries	40 watt-hr/lb

Table V
Sub-System Weight Breakdown

Hydraulic Unit

Pumps (4 ea.)	224
Motors	38
Valves	240
Plumbing	1455
N_2 Pressurization System	126
Fluid	877
Reservoirs	100
Boiler	90
Cooling Water and Tankage	463
	3613
Plus 10%	361
	3974 lb.

Auxiliary Power Unit

Turbine/Alternator (4 ea. @ 130 lb.)	520
Plumbing	45
Exhaust Lines	78
Heat Exchangers (4 ea. @ 24 lb)	·96
	739 lb.
Average Specific Fuel Consumption	3.92 lb/kw-hr
O/F	0.87

Table VI

Weight Summary: System A

	Dual Mode unit	Dual Mode system	Closed Cycle unit	Closed Cycle system	Allis-Chalmers unit	Allis-Chalmers system	General Electric unit	General Electric system
Fuel Cell Engine	59	236	178	712	276	1104	128	512
Fuel and Tankage		910		860		794		868
Water and Tankage		21		29		23		29
Radiator	90	360	79	316	63	252	80	320
Heat Exchanger	4	16	3	12	3	12	3	12
Evaporator		0		7		5		7
		1543		1936		2190		1748
Hydraulic Unit		3974		3974		3974		3974
Aux. Power Unit		739		739		739		739
Fuel and Tankage		1550		1550		1550		1550
System Total		7806		8199		8453		8011

Table VII

Weight Summary: System B

	Dual Mode unit	Dual Mode system	Closed Cycle unit	Closed Cycle system	Allis-Chalmers unit	Allis-Chalmers system	General Electric unit	General Electric system
Fuel Cell Engine	507	2028	2170	8680	3370	13480	1560	6240
Fuel and Tankage		1230		1112		1016		1160
Water and Tankage		906		932		879		1113
Radiator	78	312	67	268	47	188	71	284
Heat Exchanger	3	12	3	12	2	8	3	12
Evaporator		0		314		293		377
		4488		11,318		15,864		9186
Hydraulic Unit		3974		3974		3974		3974
Alternator	25	100	25	100	25	100	25	100
Motor	360	1440	360	1440	360	1440	360	1440
System Total		10,002		16,832		21,378		14,700

Table VIII

Weight Summary: System C

	Dual Mode unit	Dual Mode system	Closed Cycle unit	Closed Cycle system	Allis-Chalmers unit	Allis-Chalmers system	General Electric unit	General Electric system
Fuel Cell Engine	317	1268	1353	5412	2100	8400	975	3900
Fuel and Tankage		1130		994		908		1022
Water and Tankage		559		579		544		689
Radiator	92	368	68	272	49	196	71	284
Heat Exchanger	4	16	3	12	2	8	3	12
Evaporator		0		189		177		228
		3341		7458		10,233		6135
Motors	239	956	239	956	239	956	239	956
Inverters	157	628	157	628	157	628	157	628
Electric Lines	170	680	170	680	170	680	170	680
System Total		5605		9722		12,497		8399

Table IX

Weight Summary: System D

	Dual Mode unit	system	Closed Cycle unit	system	Allis-Chalmers unit	system	General Electric unit	system
Fuel Cell Unit (Same as System A)		1543		1936		2190		1748
Batteries	3350	13400	3350	13400	3350	13400	3350	13400
Hydraulic Unit		3974		3974		3974		3974
Alternators	25	100	25	100	25	100	25	100
Motors	360	1440	360	1440	360	1440	360	1440
System Total		20,457		20,850		21,104		20,662

Table X

Weight Summary: System E

	Dual Mode unit	system	Closed Cycle unit	system	Allis-Chalmers unit	system	General Electric unit	system
Fuel Cell Unit (Same as System A)		1543		1936		2190		1748
Batteries	1987	7950	1987	7950	1987	7950	1987	7950
Motors		956		956		956		956
Inverters		628		628		628		628
Lines		680		680		680		680
System Total		11,757		12,150		12,404		11,962

Table XI

Summary of Total System Weights

		P & W Dual Mode	P & W Closed Cycles	Allis- Chalmers	General Electric
System A:	Fuel Cells, APU. Hydraulic Actuation	7,806	8,199	8,453	8,011
System B:	Fuel Cells. Hydraulic Actuation	10,002	16,832	21,378	14,700
System C:	Fuel Cells. Electric Actuation	5,605	9,722	12,497	8,399
System D:	Fuel Cells, Batteries. Hydraulic Actuation	20,457	20,850	21,104	20,662
System E:	Fuel Cells, Batteries. Electric Actuation	11,757	12,150	12,404	11,962

FIGURE 1.

SYSTEM A

CONCEPT:
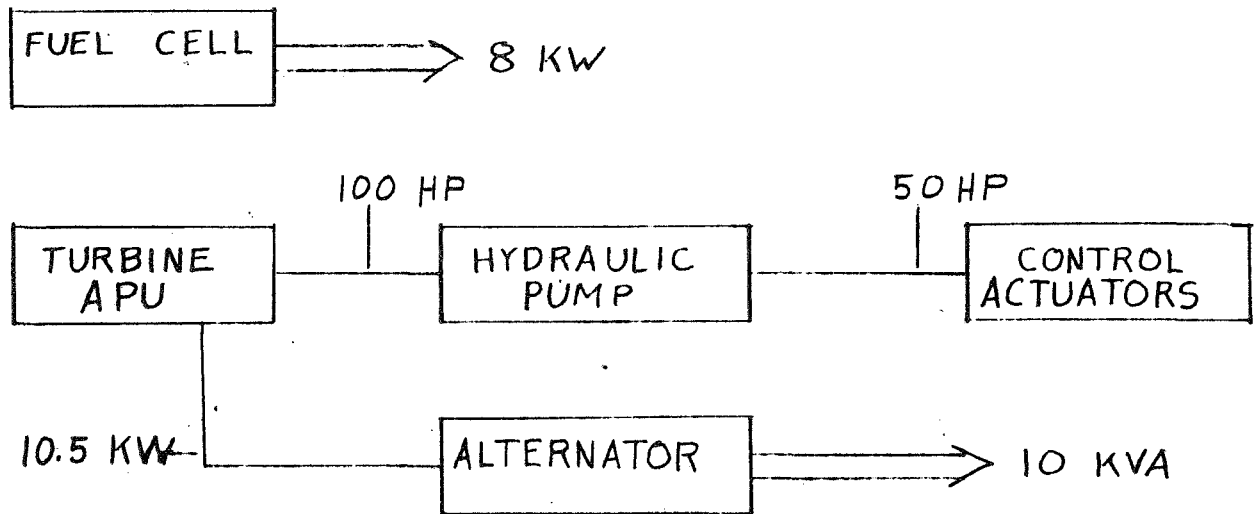
POWER PROFILE:
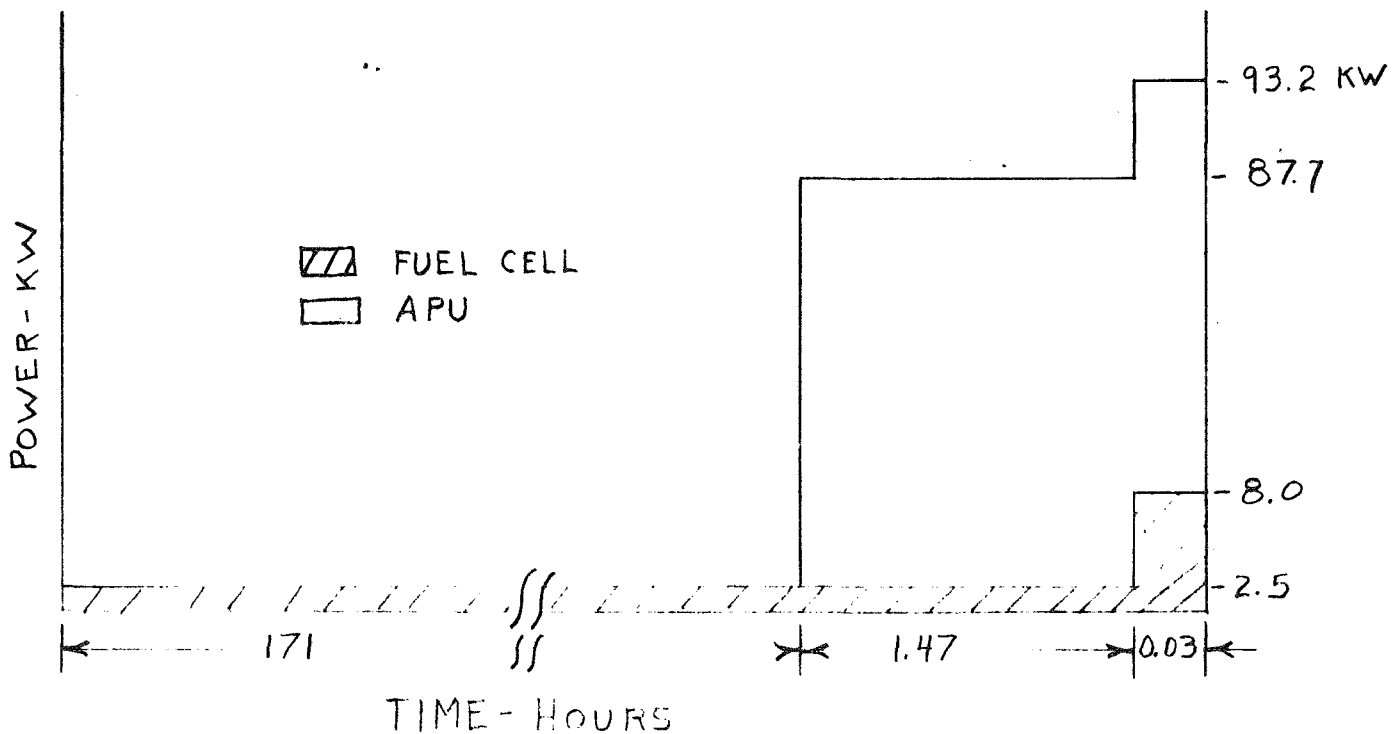
FIGURE 2

SYSTEM B

CONCEPT:


```
                    8.0 KW
                      ↑
                      |    105 HP        100 HP           50 HP
  ┌───────────┐    ┌─┐│    ┌──────────┐         ┌──────────┐         ┌──────────┐
  │ FUEL CELL │────┤ ├─────┤ ELECTRIC │─────────│ HYDRAULIC│─────────│ CONTROL  │
  │           │    └─┘     │  MOTOR   │         │  PUMP    │         │ ACTUATORS│
  └───────────┘    11.1 KW └────┬─────┘         └──────────┘         └──────────┘
                                │
                             10.5 KW
                            ┌────┴─────┐
                            │ALTERNATOR│──────────→  10 KVA
                            └──────────┘
```

POWER PROFILE:

POWER - KW (vertical axis)

- 97.6 KW
92.1
- 2.5

TIME - HOURS (horizontal axis)

171   1.47   0.03
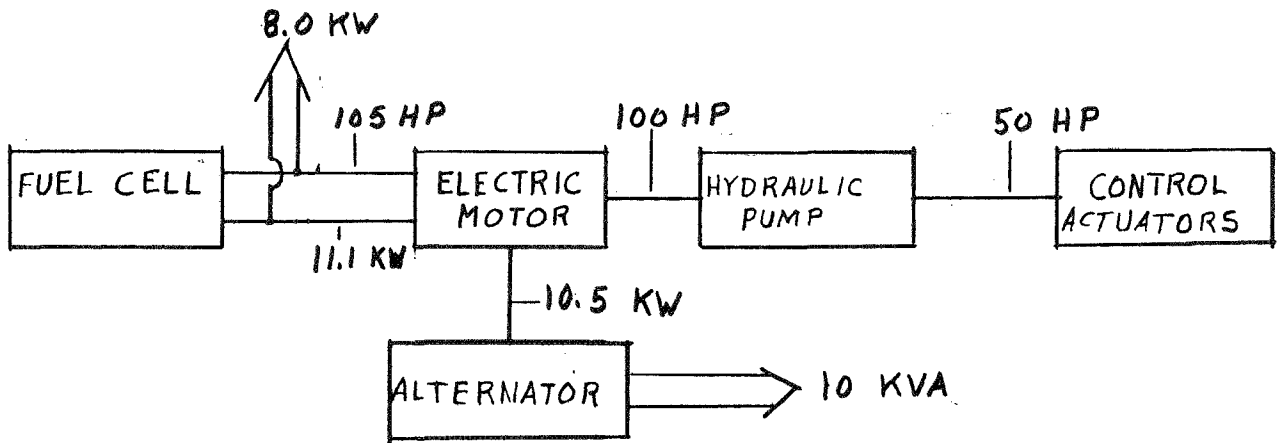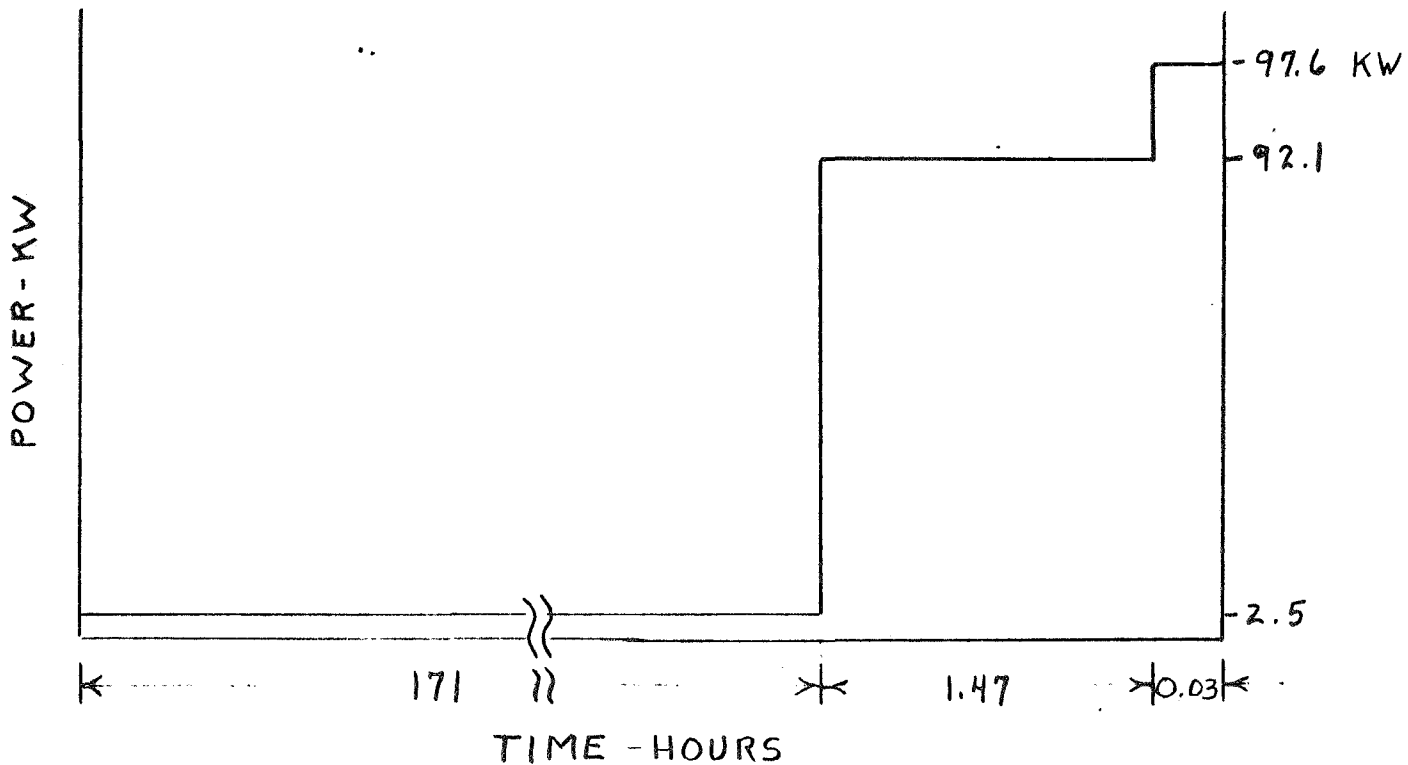
FIGURE 3

SYSTEM C

CONCEPT:

8 KW

57 HP   53 HP   50 HP

FUEL CELLS   ELECTRIC MOTORS   CONTROL ACTUATORS

10.5 KW   INVERTERS   10 KVA

POWER PROFILE:

POWER-KW (vertical axis)

- 61 KW
- 55.5
- 2.5

171

1.47   0.03

TIME - HOURS
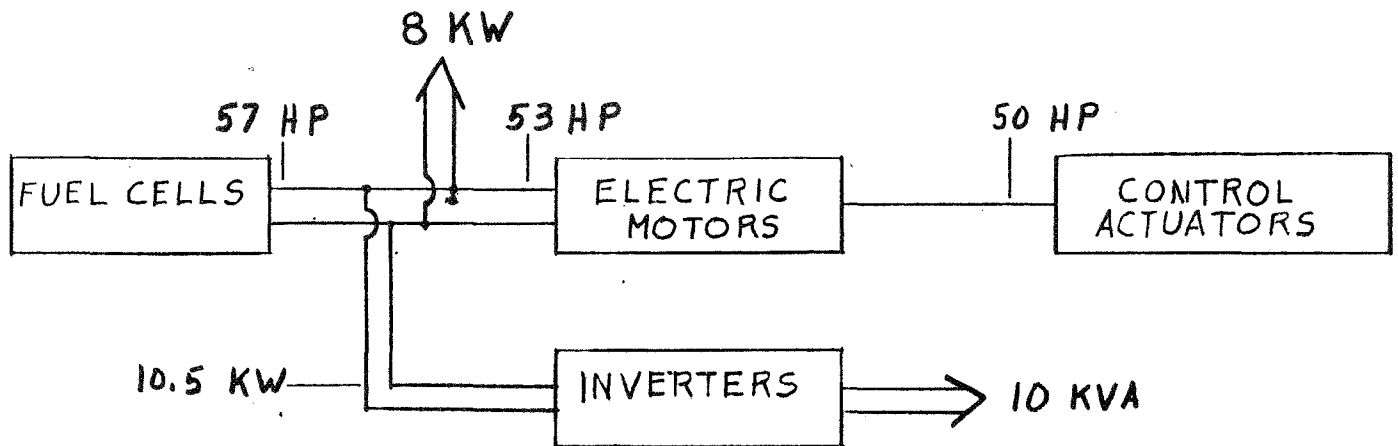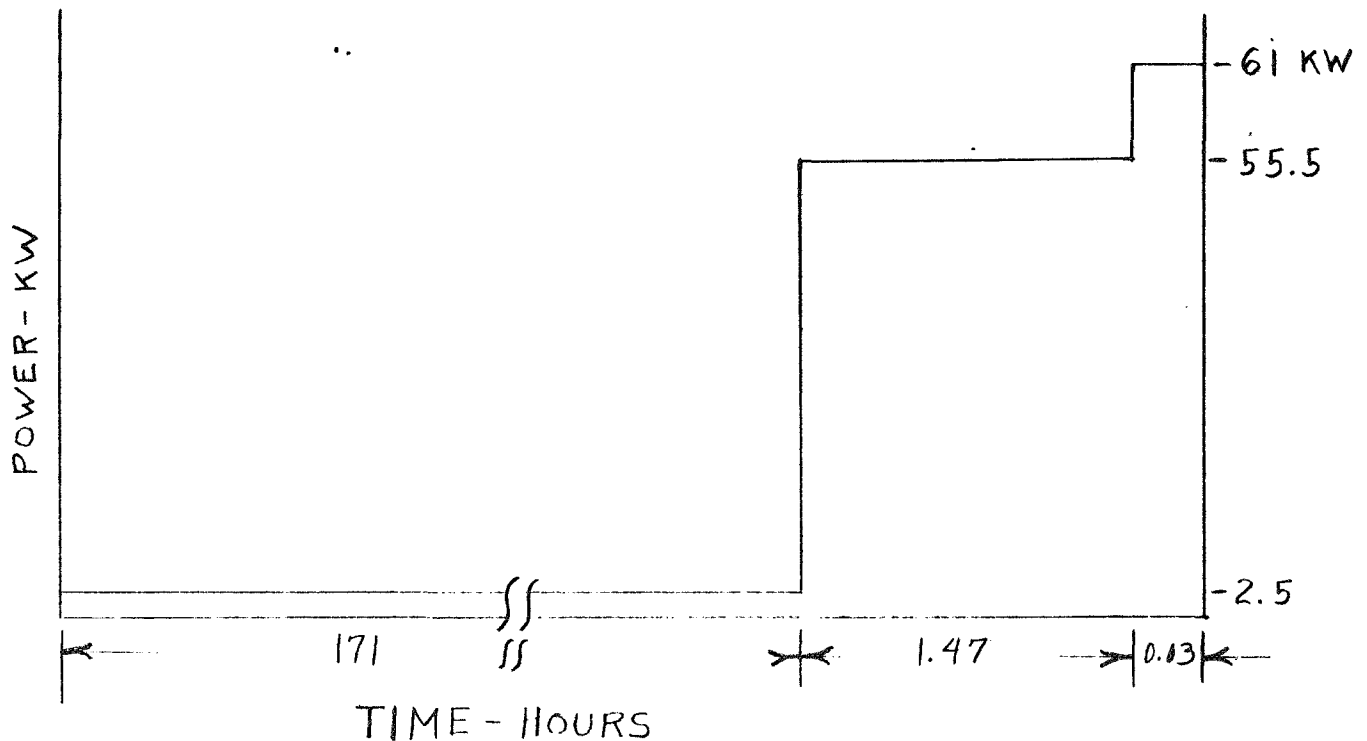
FIGURE 4.

SYSTEM D

CONCEPT:

```
┌──────────────┐
│  FUEL CELL   │ ═══════▶  8 KW
└──────────────┘

                   105 HP              100 HP            50 HP
┌──────────────┐    │    ┌──────────────┐    │    ┌──────────────┐    │    ┌──────────────┐
│  BATTERIES   │════╪════│   ELECTRIC   │────┼────│  HYDRAULIC   │────┼────│   CONTROL    │
│              │════╪════│    MOTOR     │         │    PUMP      │         │  ACTUATORS   │
└──────────────┘    │    └──────────────┘         └──────────────┘         └──────────────┘
                 11.1 KW        │
                        10.5 KW │
                        ┌──────────────┐
                        │  ALTERNATOR  │  ┄┄▶  10 KVA
                        └──────────────┘
```
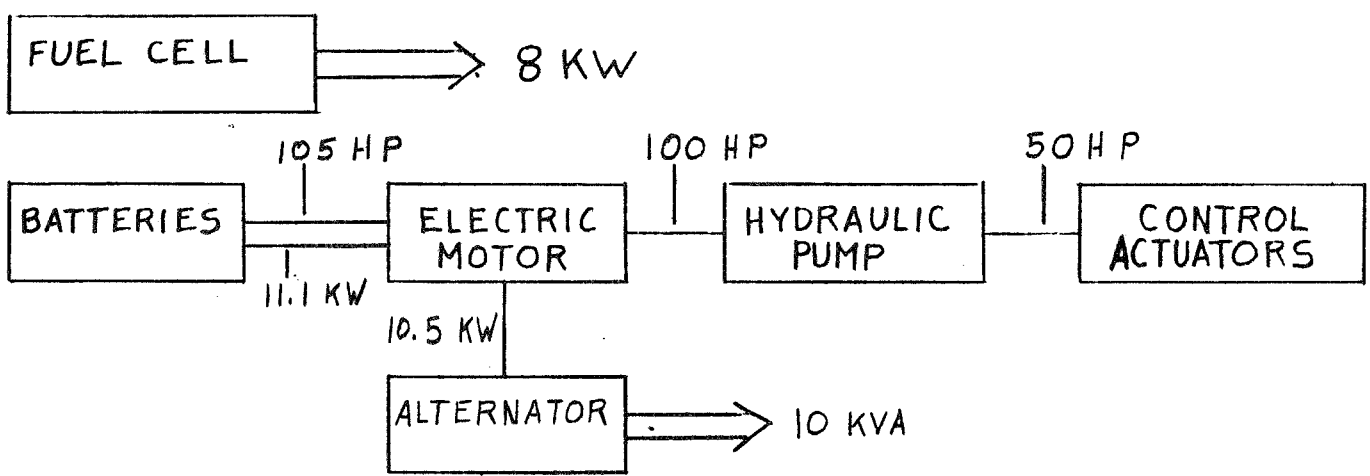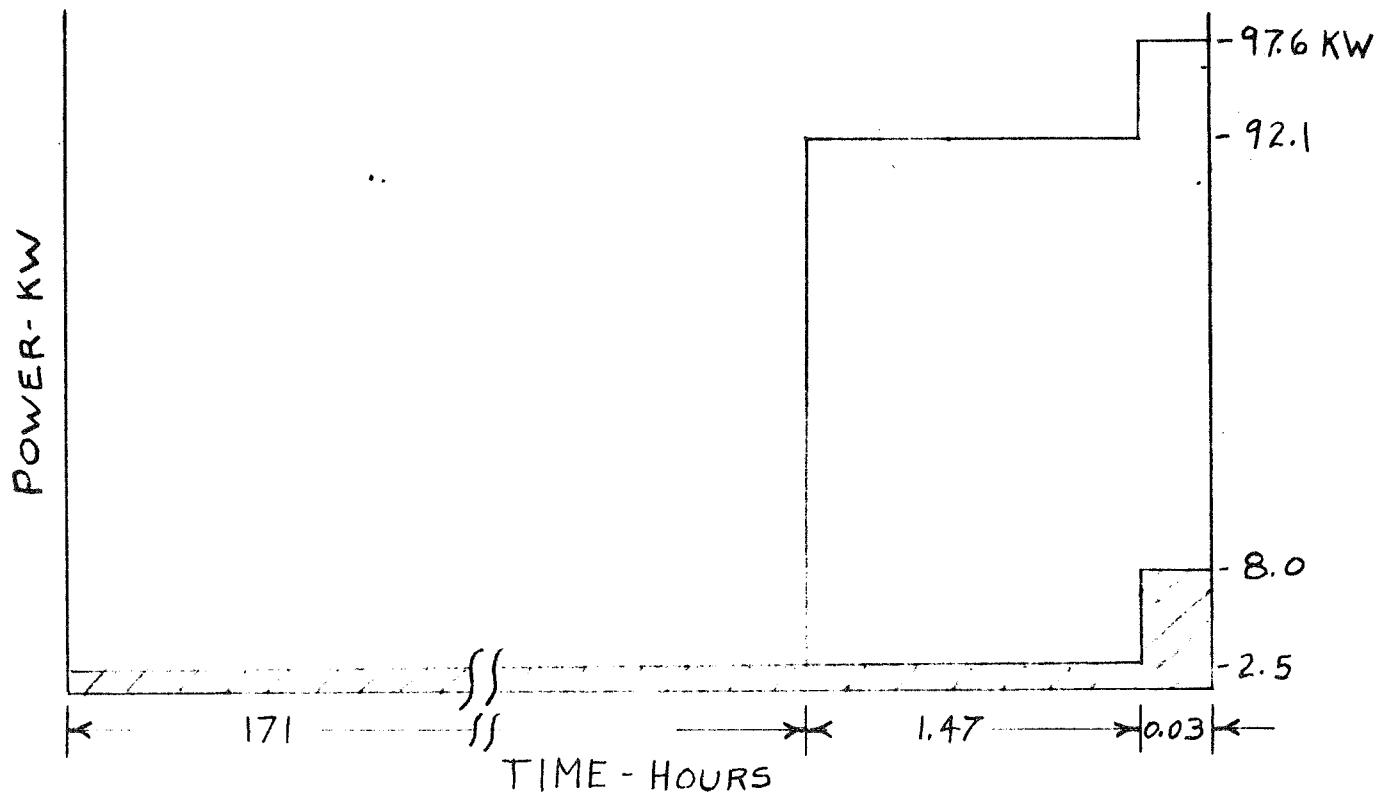
POWER PROFILE:

FIGURE 5.

SYSTEM E.

CONCEPT:

```
┌──────────────┐
│  FUEL CELLS  │ ──────────────▶  8 KW
└──────────────┘
```

```
                57 HP      53 HP                          50 HP
┌──────────────┐    │         │    ┌──────────────┐         │    ┌──────────────┐
│  BATTERIES   │────┼─────────┼────│   ELECTRIC   │─────────┼────│   CONTROL    │
│              │    │         │    │    MOTORS    │         │    │  ACTUATORS   │
└──────────────┘    │         │    └──────────────┘              └──────────────┘
                    │         │
   10.5 KW ─────────┤         │    ┌──────────────┐
                    └─────────┴────│   INVERTER   │ ──────────▶  10 KVA
                                   └──────────────┘
```

POWER PROFILE:

POWER - KW

TIME - HOURS

─ 61.0 KW
─ 55.5
─ 8.0
─ 2.5

|171 || 1.47   0.03